not at an identical speed, but with widely different velocities. The experiments with radium emanation gave similar evidence with respect to the β-rays from RaB and RaC.

Summing up the experiments which, as we have seen, confirm Wilson's results, we may say that—

1. β-rays, which are absorbed according to an exponential law, are not homogeneous.

2. β-rays must fall in velocity in traversing matter, for, if not, the absorption coefficient of any mixture of rays would decrease as the rays passed through matter.

In conclusion, I wish to express my thanks to Prof. Rutherford for suggesting these experiments and for his advice and help during their progress, and also to Dr. Boltwood, who separated and purified the sample of radium D employed in these experiments.

The Decrease of Velocity of the β-Particles on Passing through Matter.

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Introduction.

In a previous paper* it was shown that the absorption of homogeneous β-rays by matter when determined by the ionisation method does not take place according to an exponential law, as had previously been assumed, but according to a law which is practically linear.

This means that the absorption coefficient† of the rays becomes greater the further the rays penetrate the absorbing medium, and since the absorption coefficient increases with decreasing velocity of the β-rays it suggests that the rays are slowed down on passing through matter.

Some experiments were described‡ which fully confirm this view.

* Wilson, 'Roy. Soc. Proc.,' A, vol. 82, 1909.

† If β rays of intensity I fall on a layer of matter of thickness dx, the intensity is decreased by $\lambda I\,dx$, and λ is called the absorption coefficient of the rays. For an exponential law of absorption λ is constant.

‡ *Loc. cit.*, p. 625.

The following experiments were made in order to determine the manner in which the velocity of the rays decreases as they pass through matter and to test if the actual decrease observed is sufficient to account for the linear law of absorption.

Experimental Arrangement.

The general idea of the experiment was to separate out a beam of approximately homogeneous rays by means of a magnetic field, and to determine the velocity of these rays after passing through various sheets of matter by means of a second field.

The arrangement of apparatus is shown in fig. 1. A quantity of radium emanation corresponding to about 30 milligrammes radium bromide was used

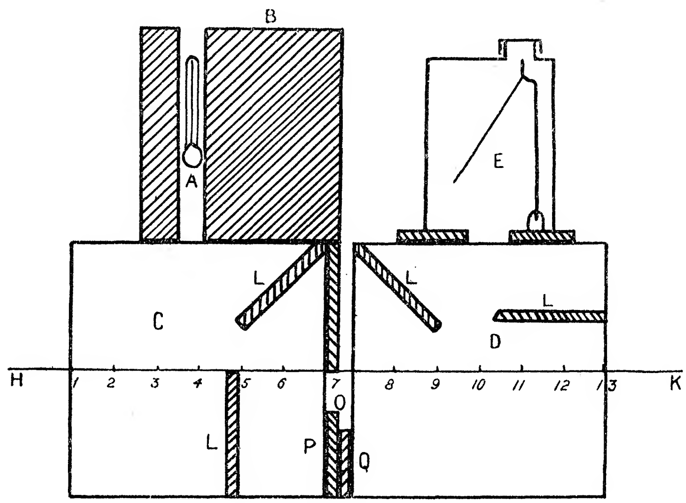

Fig. 1.

as a source of β-rays and was contained in a thin glass bulb A. This was placed in a hole 0·5 cm. diameter in a lead block B in such a manner that the rays from the active deposit could pass into the magnetic field C. The β-particles moved through the field in circular paths and passed through a hole O in a lead plate P into a second magnetic field D, where they were further deflected and made to enter an electroscope E. The mean radius of curvature in both fields was 3·5 cm. The screens L, L, L, L, were inserted in order to prevent complications due to secondary and scattered rays.

The pole-pieces of the two magnets were separated by two lead plates, P and Q. In P the hole O was cut, while in Q there was a slot in which various sheets of aluminium could be inserted to cover the hole O. The whole was securely clamped in order to prevent movements of the apparatus when the current in either electromagnet was switched on or off.

The first point to decide in connection with the apparatus is the constancy of the fields between the pole-pieces of the two electromagnets. For this purpose, readings were taken of the field strength at different points, such as those shown in fig. 1, by 1, 2, 3, . . . 13, along the line HK. The points were 1 cm. apart. The results obtained are shown in fig. 2, the positions in the field being taken as abscissæ and the strengths of the field as ordinates. We see that there is a sudden change in the field as we pass from between the pole-pieces of one magnet to between those of the other, and that the fields in each are practically uniform.

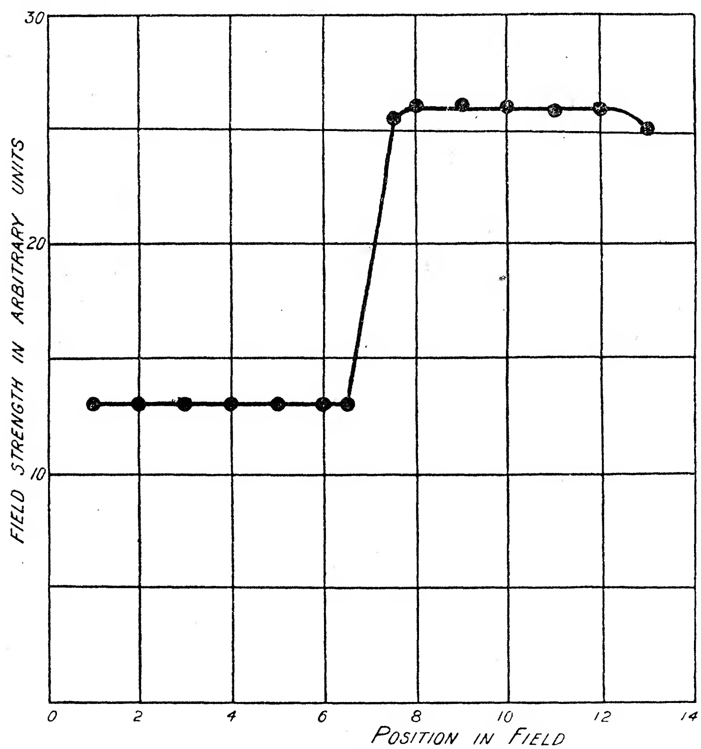

Fig. 2.

The field in each electromagnet is a function of the current in both. Thus, if the current through the electromagnet C was kept constant and that in D made to vary, changes took place in both the fields C and D. Now, in the present case, it is required that the field in the electromagnet C should be kept constant, while that in D is made to vary, so that changes in the currents exciting both electromagnets are necessary. The system was therefore calibrated as follows:—The current in the electromagnet C was kept constant, while that in D was varied, and the strengths of the fields in each were

determined by means of a Grassot fluxmeter, for each value of the current in D. A similar set of readings was taken for about ten different values of the current in C. From the results thus obtained, curves could be drawn from which the values of the currents in C and D could be adjusted so that the field in C was kept constant while that in D was made to vary.

Method of Experiment.

The method of conducting an experiment was as follows:—By passing currents of known strength through the electromagnets C and D, approximately homogeneous radiation was allowed to pass through the hole O into the magnetic field D. The field in D was varied, while that in C was kept constant, so that the same bundle of approximately homogeneous rays passed through the hole O during the whole of an experiment. The ionisation in the electroscope was determined for each value of the field in D, and the values thus obtained were plotted against the current through D. The rays were then made to pass through various sheets of aluminium placed in the slot in Q before they entered the second magnetic field, and the experiments repeated. Curves obtained in this manner are shown in fig. 3, and have well defined maxima. If the source of the rays and the

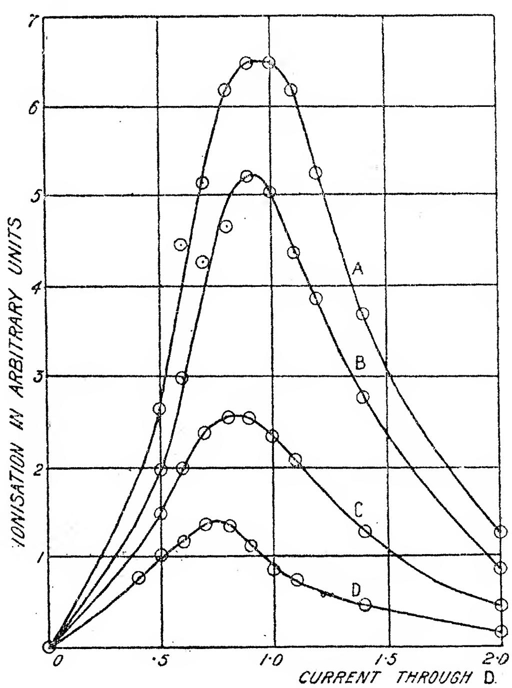

FIG. 3.

apertures between the fields and under the electroscope were infinitely small, the rays entering the second field would be quite homogeneous, and we would only get ionisation in the electroscope for one definite value of the field in D. Since the conditions of the experiment require that these should have some finite size we get instead a curve which rapidly rises to a maximum, which may be taken as a measure of the mean velocity of the rays. It will be noticed that these maximum points move to the lower fields as sheets of aluminium are interposed in the path, proving conclusively that the velocity of the rays decreases by an appreciable amount as they pass through matter. The effects observed cannot be due to heterogeneity of the rays which pass into the second field, for if this were the case, and there were no change in the velocity of the rays on passing through matter, the maximum point would move to the higher instead of the lower fields, owing to the fact that the slow rays are more easily absorbed than the rapid ones.

Schmidt* looked for this effect with the rays from radium E, which were supposed to be homogeneous. He found no change in the position of the maximum when various sheets of metal were interposed in the path of the rays before they entered the magnetic field. These rays are, according to the view put forward in my previous paper, heterogeneous, and this accounts for the fact that the maximum point does not show any appreciable change of position. The greater absorption of the slow than of the rapid rays tends to move the maximum point to the higher fields, while the decrease in velocity tends to move it in the opposite direction. The two effects are of the same order of magnitude, and no appreciable movement of the maximum point takes place.

Returning to the present experiments, if screens were placed under the electroscope instead of between the two magnetic fields, the maximum point was found to move slightly to the higher fields, on account of the rays being not quite homogeneous. This effect was not so strongly marked for the rapid as for the slow rays.

The field-strengths corresponding to the various maxima could be determined from the calibration curves, and the velocities deduced. By this means, the manner in which the velocity of the β-rays falls off with thickness of matter traversed can be determined.

When the β-particles fall on matter, a certain proportion are sent back, a certain proportion absorbed, and those which pass on do so with diminished speed. Thus, in the present experiments, we have, besides a movement of the maximum to the lower fields, a considerable decrease in the number of

* Schmidt, 'Phys. Zeit.,' 8, 1907, p. 361.

particles reaching the electroscope when sheets of matter are inserted in the path of the rays. This makes it impossible to continue measurements after the β-particles have passed through a small thickness of aluminium. Experiments were therefore carried out as follows:—Particles moving at a high speed were started with, and their velocity determined after they had passed through various thicknesses of matter. Another experiment was then started, with the initial velocity intermediate between the first and last of the former set of readings, and similar measurements made. This process was repeated until rays of such low velocity were reached, that their rate of absorption became altogether too great to admit of any accurate determination of the maxima.

Discussion of Results.

Results obtained in this manner are shown in Table I. The portions into which the table is divided refer to experiments starting with different initial points.

Table I.

Thickness of aluminium in mm.	$H\rho$ in Gauss cm.		Velocity in 10^{10} cm./sec.		Energy in 10^{-7} ergs.	
	Screen under electroscope.	Screen between fields.	Screen under electroscope.	Screen between fields.	Screen under electroscope.	Screen between fields.
0·245	5280	4980	2·85	2·83	17·6	16·2
0·489	5280	4500	2·85	2·80	17·6	14·3
0·067	4750	4250	2·819	2·78	15·2	13·5
0·245	4730	4100	2·818	2·77	15·2	12·9
0·489	4800	3620	2·820	2·71	15·2	10·6
0·731	4730	3130	2·818	2·63	15·2	8·7
0·067	3770	3690	2·73	2·72	11·4	11·1
0·245	3800	3420	2·735	2·68	11·4	10·0
0·489	3800	3000	2·735	2·60	11·4	8·1
0·067	2520	2250	2·475	2·38	6·2	5·2
0·245	2850	1950	2·565	2·25	7·5	4·1

The velocities are calculated from the formula $mv/e = H\rho$ where H is the strength of the field and ρ the radius of the path of the rays. The value of e/m was determined from the Lorentz-Einstein formula

$$\frac{e}{m} = \frac{e}{m_0}\left(1-\frac{v^2}{c^2}\right)^{\frac{1}{2}},$$

where c is the velocity of light. The value of e/m_0 is taken as $1{\cdot}74 \times 10^7$ E.M.U.*

* Bucherer, 'Phys. Zeits.,' 9, 1908, p. 755.

The corresponding values of the energy are calculated from the equation given by Einstein.*

$$E = m_0c^2 \left\{ \left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}} - 1 \right\}.$$

Now, according to the experiments described in my previous paper, the absorption of the β-rays takes place according to a linear law when measured by the ionisation. That is, the rays after passing through a given thickness of matter x have an intensity given by

$$I = k(a-x),$$

where k and a are constants.

The absorption coefficient is defined by λ where $\lambda I\,dx = -dI$, or

$$\lambda = -\frac{1}{I}\frac{dI}{dx} = \frac{1}{a-x}. \qquad (1)$$

Thus the value of λ increases as the thickness of matter increases from zero, becoming theoretically infinite when $x = a$.

In the previous paper a table was given showing the connection between λ and the velocity of the β-rays, and from it we can find the velocity of rays with any given absorption coefficient.

Now from equation (1) we can determine the absorption coefficient of rays of any initial velocity after they have passed through any given thickness of matter, and hence can deduce the corresponding velocity. Results obtained in this manner are shown in Table II, where the initial velocity of the rays is $2{\cdot}86 \times 10^{10}$ cm./sec.

Table II.

Thickness of Al in mm.	λ in cm.$^{-1}$.	Velocity in 10^{10} cm/sec.	Energy in 10^{-7} ergs.
0·00	4·7	2·86	18·6
0·51	6·2	2·80	14·3
0·83	7·7	2·75	12·0
1·03	9·1	2·70	10·4
1·20	10·8	2·65	9·2
1·34	12·7	2·60	8·1
1·48	15·4	2·55	7·15
1·58	18·2	2·50	6·5
1·66	21·3	2·45	5·9
1·72	24·1	2·40	5·4
1·78	28·6	2·35	4·9
1·82	32·3	2·30	4·5
1·86	37·0	2·25	4·1
1·88	40·0	2·20	3·8
1·95	55·5	2·00	2·75

* Einstein, 'Ann. der Physik,' June, 1907.

The results obtained in this manner were compared with those determined experimentally as follows:—Starting with rays of a certain observed velocity, we can calculate what their velocity should be after passing through various thicknesses of matter, and these results can be compared with those actually determined. Such starting points are shown in Table III in square brackets. The values of the velocities after the rays have passed through various sheets of aluminium are shown in Column 4, and the corresponding velocities calculated as above in Column 5. The various sections of the table refer to experiments with different starting points. The agreement is seen to be good, except in the case of some of the low velocities, which are difficult to determine.

Table III.

Thickness of matter in mm.	$H\rho$ in Gauss cm.		Velocity in 10^{10} cm./sec.	
	Observed.	Calculated.	Observed.	Calculated.
0	5280	5420	2·85	2·86
0·245	[4980]	[4980]	[2·83]	[2·83]
0·489	4500	4520	2·80	2·80
0	4800	4850	2·82	2·825
0·245	[4390]	[4390]	[2·79]	[2·79]
0·489	3850	3950	2·74	2·75
0·731	3340	3510	2·67	2·69
0	4630	4560	2·82	2·81
0·067	4250	4430	2·78	2·79
0·245	[4100]	[4100]	[2·77]	[2·77]
0·489	3620	3690	2·71	2·715
0·731	3130	3290	2·63	2·65
0	3770	3850	2·735	2·74
0·067	3690	3740	2·72	2·725
0·245	[3420]	[3420]	[2·68]	[2·68]
0·489	3000	3000	2·60	2·60
0·245	2750	2720	2·54	2·535
0·489	2370	2600	2·425	2·50
0·067	2250	2390	2·385	2·42
0·245	1950	2400	2·25	2·42

In the last two sections of the table the starting points are not shown, since they were different for each different thickness of matter. The position of the maximum point moved appreciably to the higher fields when sheets of different thickness were placed under the electroscope, and these positions were taken as starting points.

The experiments become very difficult when rays of low velocity are being dealt with, owing to the fact that they are both very easily scattered and very easily absorbed by the screens which are placed in their path.

The decrease of velocity with thickness of matter traversed is shown graphically in fig. 4. The curve is drawn from the results given in Table II, and the points denoted by circles are the experimental values given in

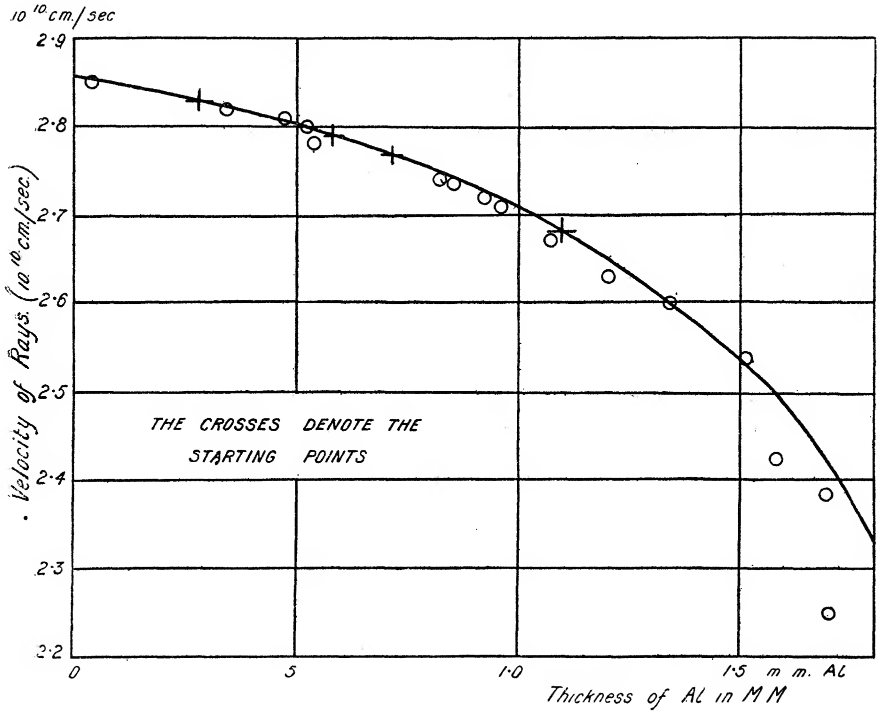

FIG. 4.

Table III. The values in square brackets are fitted on the curve, and the remaining points are determined from these starting points.

Now although the total change of velocity observed in these experiments is small it is quite definite, and since we are dealing with rays of high velocity the change in the energy and in the properties of the rays with respect to absorption are quite great. Taking the difference between the highest and lowest values of the velocity observed, the change is only from $2{\cdot}85$ to $2{\cdot}25 \times 10^{10}$ cm./sec., *i.e.*, only 21 per cent. The change of energy corresponding to this is from $17{\cdot}6$ to $4{\cdot}1 \times 10^{-7}$ ergs, or a difference of 77 per cent. The change in the value of the absorption coefficient is still more marked, for that corresponding to the higher velocity is $4{\cdot}8$ cm.$^{-1}$ while that corresponding to the lower is $35{\cdot}7$ cm.$^{-1}$, which shows that the penetrating power of the rays has been completely altered.

The Law of Decrease of the Velocity of the β-rays as they penetrate Matter.

By considerations of the energy given up by the β-particles to the matter with which they come into contact Sir J. J. Thomson* has deduced that the energy of the rays as they penetrate matter should fall off according to the law $E^2 = k(a-x)$ where E is the energy of the rays, x the thickness of matter traversed, and k and a constants. The results for the range of velocities examined are in better agreement with the formula $E = k'(a'-x)$, but it is hard to distinguish between the two, as the determinations of the low velocities are uncertain. The indirect results given in Table II agree very well with this latter equation except at the end, where the decrease of E with regard to x becomes more rapid.

Conclusion.

The experiments show that the velocity of the β-particles is appreciably reduced as they pass through matter and that the magnitude of the change is such as would be expected from the linear law of absorption.

I wish to thank Professor Rutherford for his many valuable suggestions and for his kind interest in this work.

* 'Conduction of Electricity through Gases,' 2nd edit., p. 378.